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Elena Fregonara, Sara Pattono

Dipartimento Architettura e Design, Politecnico di Torino, Torino, Italy

E-mail: *elena.fregonara@polito.it, sara.pattono@polito.it*

A sustainability indicator for building projects in presence of risk/uncertainty over time: a research experience*

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JEL: *C38, C53, D81*

Aim of the paper is to present the results of a research experience focused on the setting of a sustainability indicator in presence of risk/uncertainty over time. Firstly, a literature review of the most widespread methodologies for the evaluation of project economic sustainability in a life cycle perspective is presented, extrapolating the most relevant research lines; secondly, a four steps research experience is illustrated. The methodology for calculating a stochastic economic-environmental indicator is proposed, by adopting a stochastic Global Cost approach to solve Life Cycle Cost Analysis (LCCA). The input for the analysis are modeled through Probability Distribution Functions, while the durability of components is modeled through the stochastic approach to the Factor Method.

1. Introduction

Nowadays, the definition of methodologies to support decision-making since the early design stages in the building sector projects is at the center of the scientific debate. A relevant contribution derives from the research germinated by international regulations in energy policies. Specific research lines are founded on Circular Economy and Life Cycle Thinking principles, conceiving the project in its whole life cycle articulated in phases. These last are related to specific evaluation tools.

Specifically, the recent literature deals with the approaches for verifying the economic-environmental-energy sustainability of energy efficient interventions, both in case of new buildings and in case of retrofitting of existing heritage. From the analysis of the literature, three particularly interesting aspects emerge, considered their direct repercussions on the estimative disciplinary research:

- the necessity to model jointly economic-environmental aspects, being conscious that the results of the application of specific tools for their evaluation, when applied separately, are even opposite;

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- the necessity to internalize risk and uncertainty aspects in the evaluation processes, considered as structural elements in the real estate investments related to retrofit interventions on existing heritage or new energy efficient buildings projects;
- the necessity – strictly linked to the previous point – to model lifespans of components/systems/buildings, in terms of Service Life prediction, with a direct effect on the calculation of the (eventual) residual values.

In addition to the literature, the regulatory framework and the international standards on energy policies, specifically the sections about methodologies for supporting decision-making in building projects since the early design stages, generates relevant theoretical and methodological implications on estimative discipline. Particularly, the cost definition is considered a crucial aspect in decisions among technological options.

From these premises, the aim of the paper is to present the results of a research experience focused on the setting of an economic-environmental sustainability indicator when in presence of risk/uncertainty over time.

The paper is articulated in two parts: firstly, the recognition through the literature of the most widespread methodologies for the evaluation of project economic sustainability in a life cycle perspective is presented, extrapolating the most relevant research lines; secondly, a four steps research experience, based on the literature analysis, is illustrated.

In detail, the literature review presented is focused on:

- studies about the conjoint modeling of economic-environmental aspects, through specific quantitative indicators setup. Particularly, the conjoint verification of the economic-environmental-energy sustainability is conducted throughout: 1) the Life Cycle Cost Analysis approach (LCCA, Standard ISO 15686:2008, Buildings and constructed assets – Service-life planning, Part 5: Life Cycle Costing), for economic indicators calculation, on the basis of energy performances and Global Cost calculation (Standard EN 15459:2007 – Energy performance of buildings – Economic evaluation procedure for energy systems in building); 2) the Life Cycle Assessment approach (LCA, Standard ISO 14044:2006, Environmental Management – Life Cycle Assessment – Principles and Framework), for environmental indicators calculation, simplified for the economic analysis (Embodied Energy, Embodied Carbon, dismantling of building systems, recycled materials quantity, wastes production); 3) conjoint applications for synthetic economic-environmental indicators calculation;
- studies about risk and uncertainty treatment, assuming the distinction between risk and uncertainty in relevant costs estimation in terms of Life Cycle Cost Estimates (LCCEs), and risk and uncertainty in LCCA models. Furthermore, distinction is made between deterministic Sensitivity Analysis and quantitative Risk Analysis, assuming LCCA in conjunction with Cost-risk Analysis solved through the probabilistic approach. Focus is posed at the studies about Probability Analysis with LCCA models, assuming the literature on the Probability Distribution Functions definition;

- studies about the treatment of durability of building components, assuming the approach described in ISO 15686:2008, Buildings and constructed assets – Service-life planning, Part 8: Reference Service Life and Service Life estimation, based on the Factor Analysis. Focus is posed at the most advanced studies about the stochastic approach to the Factor Method. Special attention is devoted to the residual value estimation, strictly linked to the Service Life prediction.

Otherwise, the research experience presentation is articulated in four steps:

- application of a "simplified" LCCA. In this first step, an economic-environmental performance index is obtained through the Global Cost calculation. The environmental impacts of each alternative scenario are monetized in terms of energy performance combined with the related costs evaluation. The residual value is not considered, and input data are considered deterministically (risk and uncertainty are not included in the analysis);
- application of a "hybrid" approach to the joint use of LCCA and LCA. In this second step, only the main environmental impacts are monetized and a final synthetic economic-environmental indicator, expressed in economic terms, is calculated through the Global Cost method. The residual values of technological alternative components are considered. Input data are assumed deterministic, while a final (deterministic) Sensitivity Analysis is produced;
- application of LCCA and Risk Analysis in conjoint modality, proposing the Global Cost calculation in probabilistic terms for a stochastic economic-environmental indicator calculation. In this third step the residual value is considered, deterministically, stressing its relation with the Service Life of components/systems. All the other input data are considered affected by risk and uncertainty and treated with Probability Analysis and Monte Carlo Method. The uncertainty related to the residual value is internalized through a deterministic Scenarios Analysis;
- application of LCCA through a stochastic Global Cost calculation, in which all the input data are assumed stochastic. An economic-environmental indicator is proposed acknowledging the results of step III. The focus is posed at experimenting a stochastic approach to model the residual value in terms of Service Life. Risk and uncertainty are internalized through Probability Analysis, in this case modeling uncertainty also over time.

The paper is articulated as follows: section 2 presents the scientific background and a literature review, illustrating the research methodology, the results of the literature analysis and discussing the emerging research lines. Section 3 presents the results of a research experience articulated in four phases, stemming from the scientific background traced before. Section 4 concludes the paper.

2. Scientific background and literature review

In this section, a survey on the state-of-the-art of the studies about sustainability evaluation of building projects' life cycle is proposed. As the topic involves several research communities and requires the analysis of a large amounts of information from different fields, the work starts from a literature review covering several scientific areas as Architecture, Engineering, Economics and Mathematics. The aim is to guarantee a proper mapping of the different areas of knowledge involved in the economic and environmental sustainability evaluation of a building project, and eventually to highlight the gap among these different research contexts.

Furthermore, through the literature review the consolidated or emerging research lines are identified, focusing at the methodologies upon which recent experimentations have been conducted (or, at the time being, are on progress).

The literature review develops as follows.

2.1 Sources selection criteria and classification of publications

The literature research presented here is the result of an inclusive investigation of building sector articles in the most important open-source databases, as Scopus, Web of Science and Google Scholar. The aim of this study drives the choice of the keywords used in the databases: 'life cycle cost', 'life cycle assessment', 'risk analysis', 'building' and 'construction' in different combinations.

The collection and selection process gives origin to a list of 145 references, which can be considered as relevant publications in the international scientific context.

The publications obtained by the research in the open-access databases are classified according to five main criteria:

1) year of publication;
2) geographical area of the analysis;
3) type of publication;
4) application context;
5) scientific disciplinary sector of the research.

Each criterion is then divided in sub-criteria: the analysis on the sub-criteria, through elementary statistical indicators illustrated in section 2.2, allows to develop considerations on data and provides a first indication about the international research addresses, specifically about the LCCA and its applications.

The year of publication is the first aspect analysed in each reference. As the topic is quite new and continuously updating with the recent advancements in each research area involved, the publications are concentrated from the 1990s up today (the search was performed up to September 2018). This period of analysis is then divided in three phases, on the basis of the regulatory framework strictly linked (and in most cases preliminary) to the literature production. The definition of the Standards ISO 14040:1998, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000 about the environmental analysis through LCA approach, has greatly influenced the construction sector, so that European Union, after the publication of the CEN/TC 350 - Sustainability of Construction Works, issued the Directives 2002/91/EC and 2010/31/EU on the Energy Performance of Buildings. More recently, on 19

June 2018 the Directive (2018/844/EU) amending the Energy Performance of Buildings Directive is published. These requirements try to achieve the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building.

Thus, the period of the analysis is divided in: 1) researches carried out up to 2000, before the LCA standardization; 2) researches carried out between 2001-2010, during the years of implementation of LCA analysis (by the ISO 14044:2006) and the emanation of the Directive 2002/91/EC on Energy Performance of Buildings; 3) researches carried out from 2011 up today, after the emanation of the Directive 2010/31/EU-EPBD recast.

The geographical area of publication is defined taking into account the country and the continent of the first Author's affiliation. Considering these aspects, it is possible to identify the main researches concerned with the topics analysed in this paper, highlighting the relationship with the international norms framework.

It is also important to define the type of publication, distinguishing on one side the studies under the attention of the scientific communities and, on the other one, the issues considered also by local government authorities (the second case would be desirable). Particularly, five categories of product are identified: 1) book; 2) book's chapter; 3) article; 4) conference proceeding; 5) technical report.

Afterwards, each study is deeper analysed in order to define its content characteristics and then divided according to the application context and to the scientific disciplinary sector of the research.

Analysing the collected documents two main research lines about LCC Analysis are identified. The greater attention to environmental problems has meant that during the years the research community has tried to develop systems that take into account environmental considerations, developed through LCA approach, and economic considerations developed through LCC Analysis. On the other hand, in the greatest part of applications LCC Analysis is applied deterministically. During the years researchers have suggested to introduce Risk Analysis in conjunction with LCCA to provide a better simulation of future costs related to a building project.

Therefore, three different application contexts are identified: 1) manuscripts about LCCA in general; 2) manuscripts about LCCA in conjunction with environmental analyses, as LCA; 3) manuscripts about LCCA and Risk Analysis to evaluate the relevant factors affected by uncertainty in a building project.

As the object of this paper embraces studies from different fields, as said before, the documents are grouped according to the main scientific sectors of the related research: Architecture, Engineering, Economics and Mathematics. For each scientific area there are different disciplines involved in the economic-environmental sustainability assessment and some of them can be used in more than one application context.

As regards the Architecture sector, the discipline "Real Estate Market Appraisal and Economic Evaluation of Projects" results the mainly involved in the evaluation of the economic feasibility of a building project; it is present in studies both on LCCA and on Risk Analysis. Otherwise, the "Environmental Technology" appears frequently in manuscripts about the environmental impacts assessment of a project. The Engineering sector presents three different disciplines that can be involved in the evaluation process: "Project Management" can be properly used both in LCCA and Risk Analysis studies, while "Materials Science and Technology" and "Building Physics" are habitually used in studies about environmental issues related to buildings. Finally, the disciplines "Economic Statistics", from Economics area, and "Probability and Statistics", from Mathematics area, are frequently applied in studies concerning the Risk Analysis in order to identify and manage the uncertainty characterizing the construction sector.

2.2 Literature analysis

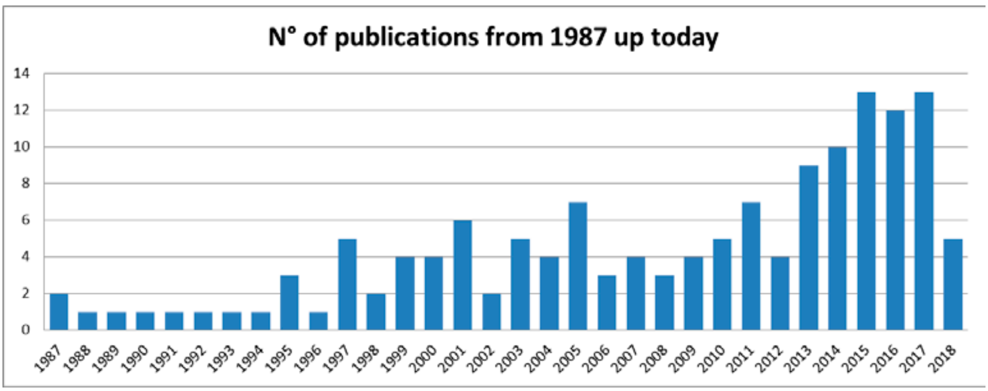
The analysis performed on the data allows to formulate some considerations.

The number of publications about LCC Analysis results continuously growing, in comparison to the first years of its development. Furthermore, it is possible to notice a close connection among the year of publication, the regulatory framework development, the geographical origin of the study and the application context.

During the early years of development of LCCA, researchers seem to focus more on improving the methodological process and particularly to resolve the issue of risks associated to building projects. Therefore, before 2000 the greatest part of articles concerns risk valuation and the different approaches for the identification and quantification of uncertainty related to projects (10%, n=14 on 28 in that period). Centrality is posed on the underestimation or overestimation of the potential consequences which can compromise the future project financing.

In the second decade identified, the studies concerning the application of single LCC Analysis have grown equally as the studies on LCCA in conjunction with Risk Analysis (9%, n=13). The economic analysis through LCCA has driven the methodology to be internationally recognized only in 2008 with the presentation of the Standard UNI EN ISO 15686:2008, Part 5. In parallel to this, the scientific

Figure 1. Production of documents on LCCA from 1987 up today.



community has suggested to introduce risk analysis to provide a better simulation of future costs related to a building project and manage the uncertainty of construction sector.

Otherwise, during this period there is a significant increase in studies concerning LCCA in conjunction with environmental analysis (11%, n=16). As previously stated, the definition of LCA methodology has greatly influenced the construction sector and the scientific community's interest seems to follow the development of the regulatory framework. The LCA methodology is universally recognized only between the end of the 1990s and the beginning of 2000 by the definition of the Standards UNI EN ISO 14040:1998, ISO 14041:1999, ISO 14042:2000, ISO 14043:2000, then modified by ISO 14044:2006, as mentioned before.

Although similar approaches to both methods of assessment are developed in the United States at the end of the 1960s, their regulation definitions and their use in the construction sector have struggled to find their own space for international diffusion. Once the regulatory framework for both methodologies is consolidated, in the decade 2001-2010, LCA and LCC Analyses know significant developments as demonstrated by the scientific production.

The current decade confirms a keen interest by the scientific community and national governments about the economic and environmental assessment of a building's life cycle and it drives the two methods to be used jointly. Today LCC Analysis is the basis for the technological–economic feasibility of a building project and more frequently this approach is used in combination with environmental analysis (23%, n=34).

It is also significant the rediscovered interest about the risk analysis in conjunction with LCCA (16%, n=23) to evaluate the relevant factors subjected to: this is probably due to the recent financial-economic crisis, that strokes hard the building sector because of the major vulnerability of the real estate market.

Analysing the total amount of the literature production for each identified application context, it is possible to notice as the majority of studies concerns LCCA in conjunction with environmental analyses application (Figure 2 – part left): this confirms the keen interest by all scientific communities in trying to manage and reduce environmental impacts caused by the construction sector.

The amount of studies concerning LCCA in conjunction with LCA application and LCCA with Risk Analysis is almost the same, while studies on LCCA in general are fewer. As previously stated, LCCA can be considered a quite consolidated methodology and nowadays most of researchers try to use it in new experimental modalities, for example introducing Risk Analysis. Furthermore, in many studies LCCA is applied deterministically, which is economically questionable: introduce Risk/Uncertain Analysis can provide a better simulation of future costs related to a building project.

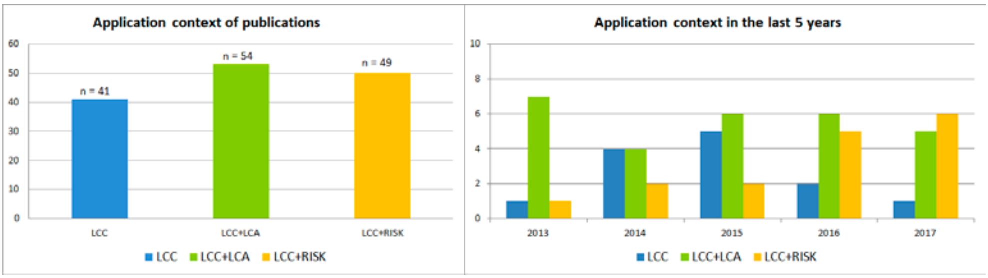
In the last five years the trend of the different application contexts identified in this study confirms the general liability of the period of analysis (Figure 2 – part right).

Even the geographical origin of investigation is related to the regulatory framework. The greatest number of publications concerning the LCC Analysis is pu-

Table 1. Distribution of studies and relative approaches during the three identified periods.

Periods and approaches	N° of publications	Percentage
until 2000	28	20,00 %
LCC	*11*	*8 %*
LCC+LCA	*3*	*2 %*
LCC+RISK	*14*	*10 %*
2001 - 2010	42	29,00 %
LCC	*13*	*9 %*
LCC+LCA	*16*	*11 %*
LCC+RISK	*13*	*9 %*
2011 - today	74	51,00 %
LCC	*17*	*12 %*
LCC+LCA	*34*	*23 %*
LCC+RISK	*23*	*16 %*

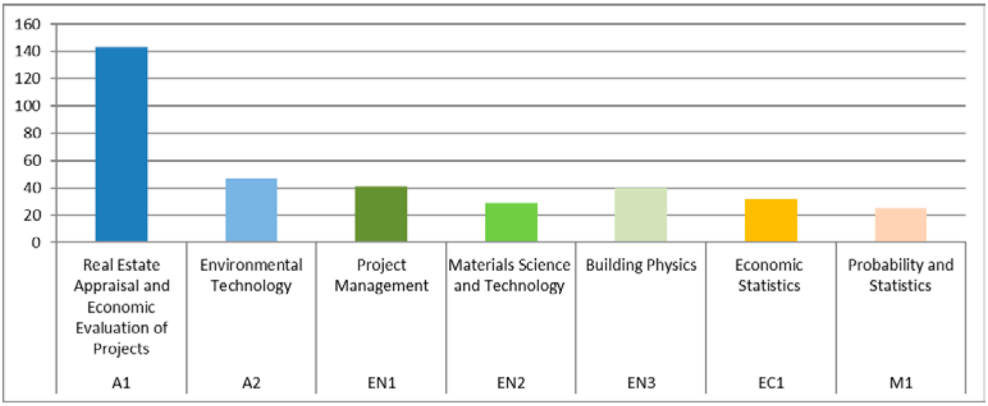
Figure 2. Part left: Total amount of documents on LCCA, LCCA+LCA and LCCA+ Risk Analysis. Part right: Total amount of documents in the last five years by application context.



blished in Europe, followed by America and Asia. The contributions from Oceania and Africa are few.

Analysing Europe and USA, it is possible to notice a great difference in publications amount between these two countries, due to the different consolidation of the approaches: in USA the LCC Analysis seems to be a common procedure that does not deserve further detailed studies, thus it is done in Europe. The EU Commission expressed the intention to applicate LCCA methodology in the building sector solely from the 2000s. In fact, in 2001 the EC has established the Task Group 4 (a specific group within the CEN/TC 350 - Sustainability of Construction Works) in order to prepare a document about the LCCA and about the modalities for integrating it into the European policies framework oriented towards sustainability in the construction sector. Subsequently, in 2006, a document about LCCA common methodology is developed by Davis

Figure 3. Number of publications dealing with the disciplines of each scientific area.



Langdon Management Consulting (Davis Langdon, 2007). The report can be considered a fundamental document for the application of the LCCA in construction sector, thus it has anticipated the emanation of international Standard ISO 15686:2008 - Part 5.

Analysing the type of publication, the higher number of documents collected are scientific articles followed by Conference proceedings and technical reports. As the methodological practice of the simple application of the LCCA can be considered consolidated, researchers aim to publish articles in scientific journals that show virtuous case-studies where LCCA is also applied in an innovative way, for example through the joint use of LCA and Risk Analysis. Moreover, bibliometric literature is widely recognized as a method for the evaluation of research performance of academics and universities, and scientific papers are expected to have a larger impact in the research community.

Coherently with the viewpoint of this work, Architecture is the main area for the scientific production; particularly the discipline Real Estate Market Appraisal and Economic Evaluation of Projects is common to all the manuscripts analysed. Environmental Technology, Project Management and Building Physics are the other disciplines appearing frequently; the high number in the latter field is due to the common application of LCC Analysis in the retrofit analysis of existing buildings, which implies studies in Energetic Engineering. Few are the documents dealing with Economics and Mathematical studies, properly used in paper about risk analysis in conjunction to LCCA.

2.3 Insights and further literature analyses

From the present review it is possible to outline some main research lines on the most widespread methodologies for the evaluation of project economic sustainability in a life cycle perspective: the Life Cycle Thinking approach has strongly influenced the methodologies for the sustainability evaluation of a building project, in particular the economic and environmental ones. These last are related to specific evaluation tools.

Beside the studies about Life Cycle Costing in general which have developed over the years (as in Flanagan & Norman, 1983; Woodward, 1997; Kishk *et al.*, 2003; Goh & Sun, 2016), in the literature considered for this paper, which is collected in parallel with the research experience exposed in section 3, it is possible to identify two main research lines:

1. studies about a conjoint economic-environmental sustainability evaluation. In particular, it is possible to divide the environmental analyses in three different categories:
   a. studies with energy analysis assessment, jointly used with LCC analysis;
   b. studies with output from LCA analysis, jointly used with LCC analysis;
   c. "hybrid" studies with main environmental impacts from energy analysis and LCA (like EE, EC, waste production, etc.) thus monetized as LCC Analysis input;
2. studies about the LCC analysis, jointly applied with Risk Analysis to manage the uncertainty issues present in the economic evaluation of building projects. Specifically, this topic can be divided in three different categories according to the approach assumed:
   a. Deterministic approach, such as Sensitivity Analysis, on main cost drivers, aiming at quantifying the effects of potential variations in input data values on the output of the analysis;
   b. Probability approach on cost-estimate input (for example the cost amount measurements), referred to Life Cycle Cost Estimates (LCCEs), and on setting the model assumptions (such as the financial inputs used and the time assumed for the analysis) referred to Life Cycle Cost Analysis. Focus is posed at the studies about Probability Analysis with LCCA models, deepening the literature on the Probability Distribution Functions definition;
   c. Probability approach, not only on input cost estimation and on model assumption, but also on the lifespan of components/systems/buildings that can affect the calculation of the residual values. Focus is posed at the Factor Analysis to solve the problem of durability of building components.

As highlighted in section 2.2, nowadays scientific literature mainly deals with the environmental-energy sustainability assessments of construction project, both in case of new buildings and in case of retrofitting of existing heritage. In this studies the main references regulations are ISO 15686-5:2008 and EN 15459:2007 for the Global Cost calculation and Directive 2010/31/EU and ISO 14044:2006 for the environmental analysis. These are selected being particularly relevant according to the estimative viewpoint.

Therefore, LCC Analysis is frequently used in combination with energy requirements analysis by the building, which can be considered the first example of conjoint economic-environmental analysis.

From the documents considered in this review, the application of energy analyses results both on single building components, as Sekhar and Toon (1998) and Cetiner & Özkan (2005), and on entire buildings as Fregonara *et al.* (2017a), adding to these the respective economic analyses on the basis of efficiency and effective criteria. A summary about the literature on LCA, life cycle energy analysis (LCEA) and LCCA studies carried out for environmental evaluation of buildings can be found in Cabeza *et al.* (2014) and D'Alpaos & Bragolusi (2018).

Furthermore, new multidisciplinary methodologies are developed to take into account environmental output from LCA analysis in LCCA applications. Many researches propose different approaches to link LCA output to LCCA, in order to support the decision making since the design stage, as for example Norris (2001), Ochoa (2002), Gu *et al.* (2008) and Haddad *et al.* (2008)

Analysing the literature, in the last years beside the conjoint use of LCC and LCA other expeditious methods have been developed to evaluate the economic and environmental sustainability of building project. An hybrid line of research try to monetize the main environmental impacts (as Embodied Energy, Embodied Carbon, waste production, etc.) in order to obtain an economic index that encloses all the considerations done in different field of study. Examples of this line can be found in Thiebat (2012) and Fregonara *et al.* (2017b)

Another important part of the scientific literature deals with LCC conjoint with Risk Analysis. The construction sector is subjected to different degrees of uncertainty that makes the deterministic LCC application questionable by many point of view: introducing the Risk Analysis can provide a better simulation of future costs related to a building project. Furthermore, analysing the documents about this topic it is possible to notice that an important part of them concerns the risk assessment techniques (mainly divided in deterministic and probabilistic approaches as state above).

This line of research refers, among the most relevant documents, to ISO 15686-5:2008 and EN 15459:2007 for the Global Cost calculation and to Davis Langdon Report and DOE Guidelines for the treatment of risk and uncertain on cost input variables.

As Marshall (1999) states, the Sensitivity Analysis is one of the most used technique as providing, in quantitative terms, the impacts of the various assumptions on the whole project. However, this technique presents some limits. Thus, over the years, other risk analysis techniques are used for the economic evaluation of a building project.

According to Sun & Chermicheal (2017), nowadays the most used risk assessment techniques are Probability Analysis and Fuzzy Sets Theory, which are mainly applied to cash-flow cost drivers and interest rate.

Over the years studies on Fuzzy Sets Theory have been proposed; this approach is considered by Sobjano (1999) a precious tool for the treatment of uncertainties due to subjective estimates in decision making models and the importance of this technique in the decision making stage is highlighted even in Kishk & Al-Hajj (2000) and Ammar (2013). More recently Ruparathna *et al.* (2017) tried to evaluate the economic sustainability of building energy retrofits using a fuzzy based approach.

However, the Probability Analysis seems more fitting, specifically in contexts characterized by instability and lack of transparency, such as the real estate market as explained in Curto & Fregonara (1999). For this reason different probabilistic approaches have been used for the economic analysis of a project, both for retrofit interventions as in Jafari *et al.* (2014) and Di Giuseppe *et al.* (2016) and new constructions as in Ergonul (2006) and Fregonara *et al.* (2018) .

According to the Probability Analysis approach, it is necessary to identify the most relevant variables, to measure their functional forms, and then to isolate and quantify the marginal contribution of each variable. Risk and uncertainty are internalized in the model through stochastic variables selected among the most significant cost items and expressed in terms of "relevant cost drivers".

The Probability Analysis can be solved through two different approaches: the analytical method and the simulation method. Particularly, the simulation method is used as an alternative to the complexity of the analytical approach and to limit the costs of the analysis; this approach deduces the probability functions using methods founded on random number generation and the output is coherently expressed in terms of Probability Distribution Functions (Maio *et al.* 2000).

In the real estate investments context, the Triangular distribution is most widely used. This simple distribution is particularly suitable when in presence of no observed data but experience allows to define the most probable value associated with a minimum and maximum value. During the years other distribution functions have been used, for example the Beta distribution by Fente *et al.* (1999): however, even if this is interesting by a theoretical point of view, after few studies in 1990's its application has been abandoned in favour of the simpler Triangular distribution, that seldom shows significant differences with the Beta distribution as explained in Chau (1995) and Johnson (1997).

Until now, all the studies analysed consider the input as stochastic variables exception for the lifespan of building components. A further step forward for the Risk Analysis applied to LCC Analysis is to consider the durability of the building and building elements as a stochastic variable, which is the most crucial aspect of the analysis. Indeed in real-life an element Service Life depends on several aspects, as the external conditions, maintenance planning and so on (ISO 15686:2008 – Part 8).

In literature three main different approaches for the Service Life estimation emerge: 1) Deterministic approaches; 2) Probabilistic approaches; and 3) Engineering approaches (Daniotti, 2010 a,b).

Fregonara & Ferrando (2018) introduce uncertainty in input variables (LCCEs) and over lifespan of systems/components/materials by using the stochastic approach to the Factor Method, considered the appropriate choice even by Aarseth & Hovde (1999) and Davies & Wyatt (2005).

Joining all these stages of analysis it is possible to obtain a complete workflow that reflects in the most realistic way the possible behaviour of a building project over time.

Summarizing, in the following Table 2 the collected references are listed in relation to the main approach in them faced.

Table 2. Summary table of references and relative topics.

Year	Author	Continent	Topic	A1	A2	EN1	EN2	EN3	EC1	M1
1987	Bromilow & Pawsey	Oceania	LCC	X		X				
	Flanagan *et al.*	Europe	LCC+ RISK	X						
1988	Gustafsson & Karlsson	Europe	LCC	X	X		X			
1989	Gustafsson & Karlsson	Europe	LCC	X	X		X			
1990	Novick	America	LCC	X		X				
1991	Gustafsson & Karlsson	Europe	LCC	X	X			X		
1992	AbouRisk & Halpin	America	LCC+ RISK	X					X	
1993	Lam	Asia	LCC	X	X		X			
1994	Warren & Weitz	America	LCC+LCA	X	X		X			
1995	Chau	Asia	LCC+ RISK	X					X	X
	Kirk & Dell'Isola	America	LCC	X						
	Ward & Chapman	Europe	LCC+ RISK	X		X				
1996	Arditi & Messiha	America	LCC	X		X				
1997	Akintoye & MacLeod	Europe	LCC+ RISK	X		X				
	Ehlen	America	LCC	X			X			
	Johnson	Europe	LCC+ RISK	X					X	X
	Mok *et al.*	Asia	LCC+ RISK	X						
	Woodward	Europe	LCC	X						
1998	Edwards & Bowen	Oceania	LCC+ RISK	X		X				
	Sekhar & Toon	Asia	LCC+LCA	X				X		
1999	Curto & Fregonara	Europe	LCC+ RISK	X		X			X	
	Fente *et al.*	America	LCC+ RISK	X		X			X	X
	Marshall	America	LCC+ RISK	X						X
	Sobanjo	America	LCC+ RISK	X		X			X	X
2000	Aya *et al.*	Oceania	LCC+LCA	X	X			X		
	Cole & Sterner	America	LCC	X						
	Kishk & Al-Hajj	Europe	LCC+ RISK	X					X	X
	Maio *et al.*	America	LCC+ RISK	X					X	X
2001	Chapman	Europe	LCC+ RISK	X		X			X	X
	Kartam & Kartam	Africa	LCC+ RISK	X		X			X	
	Kishk & Al-Hajj	Europe	LCC+ RISK	X		X			X	X
	Markeset & Kumar	America	LCC+ RISK	X		X				

Year	Author	Continent	Topic	A1	A2	EN1	EN2	EN3	EC1	M1
	Norris	America	LCC+LCA	X	X					
	Shapiro	America	LCC+LCA	X	X					
2002	Di Stefano	Europe	LCC+LCA	X	X					
	Ochoa *et al.*	America	LCC+LCA	X	X			X		
2003	Emblemsvåg	Europe	LCC+ RISK	X					X	
	Kishk *et al.*	Europe	LCC	X						
	Salem *et al.*	America	LCC+ RISK	X		X			X	
	Schmidt	Europe	LCC+LCA	X	X			X		
	Wong *et al.*	Asia	LCC	X				X		
2004	Boussabaine & Kirkham	Europe	LCC+ RISK	X		X			X	
	Gluch & Baumann	Europe	LCC	X						
	Kishk	Europe	LCC+ RISK	X					X	X
	Leigh & Won	Asia	LCC	X						
2005	Arpke & Hutzler	America	LCC+LCA	X	X			X		
	Cetiner &Ozkan	Europe	LCC+LCA	X				X		
	Christensen *et al.*	America	LCC	X		X				
	Ergonul	Europe	LCC	X						
	Kapp & Grimsheid	Europe	LCC+ RISK	X		X				
	Steen	Europe	LCC+LCA	X	X					
2006	Ergonul	Europe	LCC+ RISK	X						X
	Wiguna & Scott	Europe	LCC+ RISK	X						X
	Zou *et al.*	Oceania	LCC+ RISK	X		X				
2007	Davis Langdon Management Consulting	Europe	LCC	X		X				
	Ellingham & Fawcett	Europe	LCC	X		X				
	Nilsson & Bertling	Europe	LCC	X						
	Schade	Europe	LCC	X		X				
2008	Haddad *et al.*	America	LCC+LCA	X	X					
	Kendall *et al.*	America	LCC+LCA	X	X		X			
	Lijing *et al.*	Asia	LCC+LCA	X	X					
2009	Arja *et al.*	Europe	LCC+ RISK	X		X				
	ARUP group	Asia	LCC+LCA	X	X					
	Guoguo	Europe	LCC+LCA	X	X			X		
	Ouyang *et al.*	Asia	LCC	X				X		

Year	Author	Continent	Topic	A1	A2	EN1	EN2	EN3	EC1	M1
2010	Dattilo *et al.*	Europe	LCC+LCA	X	X	X				
	Kneifel	America	LCC+LCA	X	X		X			
	König *et al.*	Europe	LCC	X		X				
	Padgett *et al.*	America	LCC	X				X		
	Thiebat	Europe	LCC+LCA	X	X			X		
2011	Frangopol	America	LCC+ RISK	X		X				
	Hochschorner & Noring	Europe	LCC	X						
	Kim *et al.*	Asia	LCC+LCA	X	X		X	X		
	Mahliaa *et al.*	Asia	LCC	X				X		
	Marszal & Heiselberg	Europe	LCC	X						
	Menassa	America	LCC+ RISK	X			X	X	X	
	Uygunoğlu & Keçebaş	Europe	LCC	X			X			
2012	Hang *et al.*	America	LCC+LCA	X	X		X	X		
	Ihm & Krarti	Africa	LCC+LCA	X	X		X			
	Thiebat	Europe	LCC+LCA	X	X		X			
	Wang *et al.*	Asia	LCC+ RISK	X		X			X	X
2013	Addis	Europe	LCC	X						
	Ammar *et al.*	America	LCC+ RISK	X					X	X
	Capital Projects Advisory Review Board	America	LCC+LCA	X			X			
	De Angelis *et al.*	Europe	LCC+LCA	X	X		X	X		
	Fregonara *et al.*	Europe	LCC+LCA	X	X		X	X		
	Grillo *et al.*	Europe	LCC+LCA	X	X			X		
	Heijungs *et al.*	Europe	LCC+LCA	X	X		X			
	Ristimäki *et al.*	Europe	LCC+LCA	X			X	X		
	Scala	Europe	LCC+LCA	X	X			X		
2014	Bull *et al.*	Europe	LCC+LCA	X	X		X	X		
	Cabeza *et al.*	Europe	LCC+LCA	X	X			X		
	Da Silva Pereira *et al.*	America	LCC+ RISK	X		X	X		X	X
	De Jong & Arkesteijn	Europe	LCC	X						
	Department of Energy (DOE)	America	LCC	X						
	Fabbri *et al.*	Europe	LCC+LCA	X	X	X	X	X		
	Han *et al.*	America	LCC	X						
	Heralova	Europe	LCC	X		X				

Year	Author	Continent	Topic	A1	A2	EN1	EN2	EN3	EC1	M1
	Jafari *et al.*	America	LCC+ RISK	X		X		X	X	X
	Menconi & Grohmann	Europe	LCC+LCA	X	X		X	X		
	Van Gelder *et al.*	Europe	LCC+ RISK	X				X	X	X
2015	Almeida *et al.*	Europe	LCC+ RISK	X						X
	Banar & Özdemir	Europe	LCC+LCA	X		X	X			
	Becchio *et al.*	Europe	LCC + RISK	X				X		
	Ferreira *et al.*	Europe	LCC+LCA	X	X	X		X		
	Galle *et al.*	Europe	LCC	X						
	Islam *et al.*	Oceania	LCC+LCA	X	X		X			
	Islam *et al.*	Oceania	LCC+LCA	X	X			X		
	Kovacic & Zoller	Europe	LCC	X						
	Krarti & Deneuville	America	LCC	X				X		
	Liu *et al.*	America	LCC+LCA	X			X			
	Tabrizi & Sanguinetti	America	LCC	X		X		X		
	Wang & Holmberg	Europe	LCC+LCA	X	X	X		X		
	Witt *et al.*	Europe	LCC	X						
2016	Almedia & De Freitas	Europe	LCC	X						
	Becchio *et al.*	Europe	LCC+ RISK	X				X		
	Di Giuseppe *et al.*	Europe	LCC+ RISK	X					X	X
	Fregonara *et al.*	Europe	LCC+LCA	X	X	X		X		
	Goh & Sun	Asia	LCC	X						
	Gundes	Europe	LCC+LCA	X	X					
	Ilg *et al.*	Europe	LCC+ RISK	X					X	X
	Liu *et al.*	Europe	LCC+LCA							
	Mistry *et al.*	Europe	LCC+LCA	X	X		X			
	Oduyemi *et al.*	Europe	LCC+ RISK	X						X
	Plebankiewicz *et al.*	Europe	LCC+ RISK	X					X	X
	Rosato *et al.*	Europe	LCC+ RISK	X					X	X
	Thiebat	Europe	LCC+LCA	X	X	X				
2017	Daneshkhah *et al.*	Europe	LCC+ RISK	X		X			X	
	Del Giudice *et al.*	Europe	LCC+LCA	X				X		
	Di Giuseppe *et al.*	Europe	LCC+ RISK	X				X	X	
	Di Giuseppe *et al.*	Europe	LCC+ RISK	X				X		
	Fregonara	Europe	LCC+LCA	X				X		
	Fregonara *et al.*	Europe	LCC+LCA	X				X		

Year	Author	Continent	Topic	A1	A2	EN1	EN2	EN3	EC1	M1
	Fregonara *et al.*	Europe	LCC+LCA	X	X					
	Ilg *et al.*	Europe	LCC+ RISK	X		X				
	Menendez & Gharaibeh	America	LCC+ RISK	X		X	X		X	
	Pandey & van der Weide	America	LCC	X		X				
	Ruparathna *et al.*	America	LCC+ RISK	X		X			X	
	Udawattha & Halwatura	Asia	LCC+EE	X	X		X			
2018	D'Alpaos & Bragolusi	Europe	LCC+LCA	X				X		
	Fregonara & Ferrando	Europe	LCC+ RISK	X					X	X
	Fregonara *et al.*	Europe	LCC+ RISK	X	X				X	X
	Milić *et al.*	Europe	LCC+LCA	X	X			X		
	Sun & Carmicheal	Oceania	LCC+ RISK	X					X	
	Tajani *et al.*	Europe	LCC+LCA	X	X			X		

3. Research experience

Coherently with the research lines highlighted in section 2, this section points out a four-phases research experience founded on the scientific background illustrated above. The main scientific sectors are considered, as well as the interdisciplinary viewpoint stressed before.

The four steps, which are deeply illustrated in related articles produced in the period 2016-2018, are summarized as follows.

Phase I

The first research phase is presented presented by Fregonara *et al.* (2017b). In this study, a simplified LCCA is applied for the retrofit of a two-storey family residential building in order to identify the optimal scenario among a set of different technological solutions, aimed at reducing the energy requirements for the building. The simplified LCC is applied through a two-phase approach:

1. energy evaluation, based on the definition of energy efficiency solutions and the definition of different scenarios obtained through different combinations of technological solutions. For each scenario the primary energy consumptions are calculated;
2. economic evaluation, based on the calculation of the Global Cost and economic performance indexes (through a 'simplified' Life Cycle Costing approach) for each scenario identified, followed by the identification of the most viable solution from both energy and economic viewpoint.

The Standard ISO 15686–5:2008 mentioned before is used as the methodological reference for the LCCA approach. The Global Cost concept is the basis of

LCCA, as defined in the Standard EN 15459:2007 and in the Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012, following the Directive 2010/31/EU – EPBD recast. Assuming the "global cost method", the initial investment and the sum of annual and disposal costs are considered. The residual value of the components, with a life-cycle longer than the building lifetime, would be deducted, as shown in Equation (1):

$$C_G(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) R_d(i) \right) - V_{f,\tau}(j) \right] \tag{1}$$

where: $C_G(\tau)$ = global cost (referred to starting year τ_0); C_I = initial investment costs; $C_{a,i}$ (j) = annual cost during year i of component j, including annual running costs (energy costs, operational costs, maintenance costs) and periodic replacement costs; R_d (i) = discount rate during year i; $V_{f,\tau}(j)$ = residual value of the component j at the end of the calculation period, referred to the starting year.

Running costs are considered for the whole calculation period, which appropriate calculation is a very delicate step. Usually, the calculation period is determined with regard to the estimated life-cycle of a building and its technological components, accounting for the guidelines provided in the Commission Delegated Regulation (EU) No 244/2012 concerning the time period for the calculation, and the values set in European Standard EN 15459:2007 (Annex A) concerning the lifetime of the elements of the building envelope and systems.

The costs over the calculation period are discounted, through the discount factor R_d as in the following Equation (2):

$$R_d(p) = \left(\frac{1}{1 + r/100} \right)^p \tag{2}$$

where: p is the number of years starting from the initial time, r is the real discount rate, defined according to the country in which the analysis is conducted.

In this first study, a 'simplified' Global Cost calculation is performed, according to the following assumptions: the initial investment costs are related to heating, cooling, electric lighting and DHW systems, referred to specific technologies; the relevant costs are represented by operational costs and maintenance costs; the residual value of asset or materials or components and disposal costs, as said, are not considered. Thus, the LCCA is resolved through the Equation (3):

$$LCC = C_I + \sum_{t=0}^{N} \frac{C_o + C_m}{(1+r)^t} \tag{3}$$

where: LCC is the Life Cycle Cost; C_I the investment costs; C_o the operational and energy costs, C_m the maintenance costs; t the year in which the cost occurred and

N the number of years of the entire period considered for the analysis; r the discount rate.

Knowing data on the energy performance of the building, referred to a set of technological scenarios with different costs and performances, through LCCA the most viable alternative in economic and in energy performance terms is selected.

The economic indicator Net Present Value (NPV) is calculated for every scenario, with respect to the starting year τ_0. Furthermore, other economic indicators – Net Savings (NS), Simple Pay-Back Period (SPB), Discounted Pay-Back Period (DPB), Saving to Investment Ratio (SIR), Adjusted Internal Rate of Return (AIRR), are calculated for the alternative scenarios, compared to the "base case" 0.

Summing up, in this first experience:

- the environmental analysis, through the energy efficiency, is combined with the related costs evaluation, representing a first step in the construction of an environmental-economic performance index;
- the residual value is not considered;
- the input data are considered deterministically. Risk and uncertainty are not included in the analysis.

Phase II:

In this step the conjoint use of environmental and economic analysis is experimented, as illustrated in Buildings (Fregonara *et al.*, 2017c). In this study a "synthetic economic-environmental indicator" is proposed, in order to support the decision making between two alternative technological solutions (i.e. a window system with timber and aluminum frame) in a new office building. The analysis takes into account both economic and environmental impacts through a three-steps workflow:

1. Step 1 - Environmental Indicators within LCA and LCT: calculation of environmental indicators through LCA analysis. For each technological options specific environmental parameters are required, such as Embodied Energy (EE), Embodied Carbon (EC), Level of Disassembly (LD), Recycled Materials index (RM) and wastes production;
2. Step 2 - Economic Indicators with LCC Analysis: LCCA application, performed considering firstly, the residual value of the two alternative technological components (supposed with equal energy performance) at the end of the analyzed period, and, secondly, each input data (i.e. cost drivers, financial parameters and time) is treated deterministically;
3. Step 3 - Economic-Environmental Synthetic Indicator: calculation of a synthetic economic-environmental indicator, through the monetization of environmental indicators into economic parameters in order to define the best technological solution.

Notice that the methodology proposed in this study can be considered a "hybrid" approach to the joint use of LCCA and LCA analysis. In fact, only the main environmental impacts are monetized and the results are expressed in economic terms.

In the study, the NPV is calculated allowing to consider the cost items referred to the different life cycle stages, including the end-of-life stage. The eventual residual values of each component can be included. Focus is posed at the end of life stage, considering the dismantling costs and disposal costs as relevant cost items. Furthermore, it is considered the same energy performance for each design option, in order to emphasize the building components maintenance and the end of life stage. Therefore, the LCC approach is resolved according to Equation (4):

$$C_G = C_I + \sum (C_m + C_r)/(1+r)^t + (C_{dm} + C_{dp} - V_r)/(1+r)^N \quad (4)$$

where: C_G is the Life Cycle Cost; C_I the investment costs; C_m the maintenance cost, C_r the replacement cost; C_{dm} the dismantling cost and C_{dp} the disposal cost; V_r the residual value; t the year in which the cost occurred and N the number of years of the entire period considered for the analysis; r the discount rate.

As said before, a synthetic economic-environmental indicator is proposed, calculated through the Global Cost method and expressed in monetary terms, able to represent environmental and economic impacts previously calculated through LCA and LCCA. In detail, a set of environmental indices are monetized: dismantling connections performance, quantity of recycled materials, waste produced. All these costs items are summed to Global Cost, as in the following equation:

$$C_{GEnEc} = C_I + C_{EE} + C_{EC} + \sum (C_m + C_r)/(1+r)^t + (C_{dm} + C_{dp} - V_r)/(1+r)^N \quad (5)$$

where: C_{GEnEc} is the Life Cycle Cost including environmental and economic indicators; C_I the investment costs; C_{EE} the costs related to Embodied Energy; C_{EC} the costs related to the Embodied Carbon; C_m the maintenance cost, C_r the replacement cost; C_{dm} the dismantling cost and C_{dp} the disposal cost; V_r the residual value; t the year in which the cost occurred and N the number of years of the entire period considered for the analysis; r the discount rate.

Concludes the study a deterministic Sensitivity Analysis application, aiming at quantifying the effects of potential variations in input data values on the output of the analysis (on the Global Cost): specifically, uncertainty is related to the environmental impacts (EE and EC), to the discount rate, and finally to residual value, dismantling costs and disposal costs.

Summing up, in the second phase of the research experience:

- through the application of a simplified conjoint LCCA and LCA approach, a synthetic economic-environmental indicator expressed in economic terms, is calculated, by means of the Global Cost method and including the EE and EC expressed in monetary terms;
- the residual value is calculated;
- the analysis is conducted assuming deterministic input data. A final deterministic Sensitivity Analysis is produced.

Phase III:

Focusing the attention on the economic aspects of these research, the third step can be retraced in the experience published on Sustainability (Fregonara *et al.*, 2018a). This study is based on the model illustrated in Phase II, but developed on a probabilistic basis, aiming at the calculation of a stochastic economic-environmental index. It requires the conjoint use of LCCA and Risk Analysis, distinguishing between:

1. Life-Cycle Cost Estimates (LCCEs), referred to the uncertainty in the application of cost-estimating procedures due, for example, to the uncertainty in cost amount measurements;
2. Life-Cycle Cost Analysis (LCCA), referred to the uncertain components that could affect the application of the model, for example, the time horizon for the analysis, the financial inputs, and so forth.

In this study, the application of LCCA in conjunction with Risk Analysis is solved with the Probability Analysis, in turn solved through the Monte Carlo Method. The Probability Analysis seems more fitting, specifically in contexts characterized by instability and transparency, such as the real estate market. The variables are considered as random elements subjected to the uncertainty of economic systems and the flexibility of decision-makers involved in the building process.

Cost items related to the environmental impacts (monetized) are summed to Global Cost, as in Equation (6):

$$C_{GEnEc} = C_I + C_{EE} + C_{EC} + \sum (C_m + C_r)/(1 + r)^t + (C_{dm} + C_{dp} - V_r)/(1 + r)^N \qquad (6)$$

where C_{GEnEc} is the life-cycle cost including environmental and economic indicators; C_I is the investment costs; C_{EE} is the costs related to Embodied Energy; C_{EC} is the costs related to Embodied Carbon; C_m is the maintenance cost; C_r is the replacement cost; C_{dm} is the dismantling cost; C_{dp} is the disposal cost; V_r is the residual value; t is the year in which the cost occurred; N is the number of years of the entire period considered for the analysis; r is the discount rate.

The residual value V_r in this study is represented by the difference between the entire period of the analysis and the specific Service Life of components considered. The residual value is considered as a deterministic input, and, through an empirical modality, three different lifespan scenarios are defined, representing the possible temporal variability of the components. Thus, three different residual values are obtained.

In order to identify the change of an estimated cost when an assumption changes, a deterministic sensitivity analysis is carried out, for assessing the outcomes in global cost calculations for the considered solutions. The sensitivity of outcomes to the variability in the economic input parameters is quantified, specifically related to: the end-of-life stage (residual value, dismantling costs, and disposal costs), the environmental impacts (Embodied Energy and Embodied Carbon), and the discount rate.

In order to exceed the limits of the deterministic Sensitivity Analysis, which follows an empirical approach based on the variation of one input at a time and, frequently, affected by subjectivity in defining alternative scenarios, a formal quantitative risk analysis resolved through the Probability Analysis approach is proposed.

This implies the preliminary identification of the relevant cost drivers or critical input variables, expressed through stochastic variables in the evaluation of economic–financial and energy–environmental sustainability. The model output is calculated in terms of stochastic global cost (as in Equation 7) and through the relative probability distribution:

$$\hat{C}_{GEnEC} = \hat{C}_I + \hat{C}_{EE} + \hat{C}_{EC} + \sum(\hat{C}_m + \hat{C}_r) / (1 + \hat{r}) + \hat{C}_{dm} + \hat{C}_{dp} - Vr) / (1 + \hat{r})^N \quad (7)$$

where $\hat{C}_{GEnEC}$ is the Life-Cycle Cost including environmental and economic indicators expressed in stochastic terms; $\hat{C}_I$ is the stochastic investment costs; $\hat{C}_{EE}$ is the stochastic costs related to Embodied Energy; $\hat{C}_{EC}$ is the stochastic costs related to the Embodied Carbon; $\hat{C}_m$ is the stochastic maintenance cost, $\hat{C}_r$ is the stochastic replacement cost; $\hat{C}_{dm}$ is the stochastic dismantling cost and $\hat{C}_{dp}$ is the stochastic disposal cost; Vr is the residual value; t is the year in which the cost occurred; N is the number of years of the entire period considered for the analysis; and $\hat{r}$ the stochastic discount rate.

Notice that the term V_r, in this simulation, is expressed as a deterministic input. An empirical modality is predisposed by setting three alternative scenarios with three different associated Service Lives, assuming that the different lifespans give origin to three different residual values; meanwhile, these allow to model the temporal variability of the components.

Furthermore, notice that the components are supposed with the same energy performance, in order to select the preferable alternative from a sustainability viewpoint. The EE and the EC that the realization implies are considered, in relation to both the service life of the components (as maintenance costs and replacement costs), and to the end-of-life phase. Therefore, the focus is not on the energy performances of the components but on the characteristics of the constructive/executing process, including the environmental impacts in the realization phase (construction) and in the management phase (use–maintenance–adaptation).

Thus, in the third research phase:

- the Global Cost model presented in step II is proposed in probabilistic terms, by the conjoint application of LCCA and Risk Analysis, aimed at calculating a stochastic economic-environmental indicator;
- the residual value is considered, stressing its relation with the Service Life of components/systems;
- risk and uncertainty are considered in each input data, exception for the residual value. The uncertainty related to the residual value is considered, and solved through a deterministic Scenarios Analysis.

Phase IV:

The last step of this research experience is illustrated by Fregonara *et al.* (2018b). In this study uncertainty in input variables (LCCEs) and over time is introduced, paying special attention towards uncertainty in durability of systems/ components/materials.

The work proposes a methodological approach aimed at modelling lifespans as stochastic input variables, by using the stochastic approach to the Factor Method. This last is considered as an advanced modality based on the simple Factor Method, presented in the ISO 15686:2008 – Part 8 for estimating the Service Life of a building component. The Estimated Service Life is calculated by multiplying its Reference Service Life by a set of factors that can potentially influence the durability, related to specific conditions. The values of the factors are not quantified on the basis of laboratory experiments on specific components, but on hypothesis based on data deducted by the literature.

Subsequently a set of sub-factors related to each factor is individuated, on the basis of the literature on topic; the specific sub-factors are linearly combined among them for representing the synthetic factors, as indicated by literature. In this fourth work, a simplified solution is adopted by assuming hypothesis on the factors' entity, in relation to qualitative considerations (about use conditions, use environment, component quality). All factors are considered as stochastic input, exception for RSL (point data), as in Equation (8):

$$\widehat{ESL} = RSL * \hat{A} * \hat{B} * \hat{C} * \hat{D} * \hat{E} * \hat{F} * \hat{G} \quad (8)$$

where $\widehat{ESL}$ represents the stochastic Estimated Service Life of a component, RSL represents the Reference Service Life, $\hat{A}$ represents stochastically the quality of materials and components, $\hat{B}$ represents stochastically the design level, $\hat{C}$ represents stochastically the work execution level, $\hat{D}$ represents stochastically the indoor environment conditions, $\hat{E}$ represents in stochastic terms the outdoor environment conditions, $\hat{F}$ stochastically the in-use conditions, $\hat{G}$ represents stochastically the maintenance level.

The stochastic ESL calculation permits to rewrite the Equation (7) as follows (Equation 9):

$$\hat{c}_{GEnEC} = \hat{c}_I + \hat{c}_{EE} + \hat{c}_{EC} + \sum(\hat{c}_m + \hat{c}_r) / (1 + \hat{r})t + (\hat{c}_{dm} + \hat{c}_{dp} - \hat{V}_r) / (1 + \hat{r})^N \quad (9)$$

where $\hat{c}_{GEnEC}$ is the Life-Cycle Cost, including environmental and economic indicators expressed in stochastic terms; $\hat{c}_I$ is the stochastic investment costs; $\hat{c}_{EE}$ is the stochastic costs related to Embodied Energy; $\hat{c}_{EC}$ is the stochastic costs related to the Embodied Carbon; $\hat{c}_m$ is the stochastic maintenance cost, $\hat{c}_r$ is the stochastic replacement cost; $\hat{c}_{dm}$ is the stochastic dismantling cost; $\hat{c}_{dp}$ is the stochastic disposal cost; $\hat{V}_r$ is the stochastic residual value; t is the year in which the cost occurred; N is the number of years of the entire period considered for the analysis; and $\hat{r}$ is the stochastic discount rate.

The residual value is considered in this last step as a stochastic input, being obtained through the stochastic ESL calculation.

To resolve Equation (10) the same steps adopted in the previous work are proposed; differently, the stochastic residual value $\hat{V}_r$ is calculated by applying the stochastic FM. Summarizing, the steps of the analysis performed are the following:

a) Estimated Service Life determination through stochastic approach to the Factor Method. This step, in turn, consists in the following passages: 1) Reference Service Life assumption, in which the RSL of component is defined (estimates based on empirical laboratory tests, developed by the manufacturers); 2) Individuation of the Factors for FM application, on the basis of the literature on topic and on hypothesis based on data deducted by the literature; hypothesis for Factor values determination and individuation of alternative scenarios; 3) individuation of the distribution type and PDFs calculation through Monte Carlo Method; 4) Stochastic Estimated Service life calculation, through Monte Carlo Method, on the basis of the stochastic Factors defined above; 5) best fit distribution calculation to obtain a PDF related to the $\hat{S}$ (the preferable distribution function deducted by a ranking of distributions based on the results of statistic measures calculations);

b) introduction of Stochastic Service Lives in LCCA, as input data. Passage 6) Recalculation of the results of LCCA using the PDF of the $\hat{S}$ as input data for the resolution of the Equation (10);

c) calculation of LCCA results and final considerations. Passage 7) definition of the best fitting distribution function for the output values calculated in the previous passage and results interpretation.

Thus, in the fourth phase of the research experience:

- for the calculation of the economic-environmental indicator the Global Cost model defined in step III is assumed;
- the residual value is the central aspect of the study: it is considered in relation to the Service Lives of components, and it is treated according to the Factor Method assuming the set of factors able to influence the durability of the components themselves;
- risk and uncertainty are extended to all the terms of the Global Cost, including the residual value: uncertainty in residual value is transposed in uncertainty in Service Lives (durability of components), and a stochastic approach to the Factor Method is proposed to model it in LCCA, in stochastic terms.

5. Conclusions

This work offers insights into the state of knowledge on application of LCC Analysis for the economic sustainability evaluation of building projects, and reports how this topic is being explored globally.

The review shows that the issues related are under a growing interest of research communities with an increasing production of scientific papers. The most recent and emerging research lines are addressed towards the integrations of economic and environmental analysis, by applying jointly LCCA and LCA for economic and environmental sustainability respectively. Modeling environmental and economic analyses is possible but often they lead to opposite results: the best environmental solution does not always correspond to the best economic one. For this reason, a joint analysis is suggestable. A "global" performance indicator, able to synthetize simultaneously the multiple dimension of sustainability is a first relevant aspect investigated by researchers. Obviously, a multidisciplinary viewpoint is required, as the multi-sectorial literature production demonstrates.

Besides, the uncertain conditions in the building sector open the necessity to develop approaches able to model risk. Until now, some variables involved in the analyses are treated in stochastic terms, but in many cases related only to input values. This is questionable from many viewpoints; it is impossible to forecast exactly the socio-economic context where the building operations will take place, and what their consequences will be on the project itself, but also the durability of components can perturb significantly the results of the analysis. This imply the effort to introduce uncertainty over time, as the progress of the research is demonstrating that decision-making processes can be sensibly influenced when in presence of alternative technological project scenarios.

References

Aarseth L.I., Hovde P.J. (1999). *A stochastic approach to the Factor Method for estimating service life*. In Durability of Building Materials and Components 8. In Lacasse M.A. & Vanier, D.J. (Eds.), Institute for Research in Construction, Ottawa, ON, Canada.

AbouRizk S.M., Halpin D.W. (1992). Statistical Properties of Construction Duration Data. *Journal of Construction Engineering and Management* 118 (3): 525-544.

Addis M. (2013). Improvement of energy consumption and LCC optimization in a single-family house - Comparison of two cases: Denmark and Italy. Master Thesis, Politecnico di Torino.

Ahuja H.N., Dozzi S.P., AbouRizk S.M. (1994). *Project Management. Techniques in Planning and Controlling Construction Projects*. John Wiley and Sons (2nd edition). New York, NY, USA.

Akintoye A.S., MacLeod M.J. (1997). Risk analysis and management in construction. *International Journal of Project Management* 15(1): 31-38.

Almeida R., Ramos N., Manuel, S. (2015). Towards a methodology to include building energy simulation uncertainty in the Life Cycle Cost analysis of rehabilitation alternatives. *Journal of Building Engineering* 2: 44-51.

Almeida R., De Freitas V.P. (2016). An insulation thickness optimization methodology for school buildings rehabilitation combining artificial neural networks and life cycle cost. *Journal of Civil Engineering and Managemen*t 22(7): 915-923.

Ammar M., Zayed T., Moselhi O. (2013). Fuzzy-Based Life-Cycle Cost Model for Decision Making under Subjectivity. *Journal of Construction Engineering and Management* 139: 556–563.

Arditi D.A., Messiha H.M. (1996). Life-Cycle Costing in Municipal Construction Projects. *Journal of Infrastructure Systems* 2: 5-14.

Arja M., Sauce G., Souyri B. (2009). External uncertainty factors and LCC: A case study. *Building Research & Information* 37(3): 325-334.

Arpke A., Hutzler N. (2005). Operational Life-Cycle Assessment and Life-Cycle Cost Analysis for Water Use in Multioccupant Buildings. *Journal of Architectural Engineering* 11(3): 99-109.

ARUP GROUP (2009). Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) Tool for Commercial Building Developments in Hong Kong. Hong Kong, China.

Aya L., Bamford N., Charters B., Robinson J. (2000). Environmentally sustainable development: a life-cycle costing approach for a commercial office building in Melbourne, Australia. *Construction Management and Economics* 18(8): 927-934.

Banar M., Özdemir A. (2015). An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods. *Transportation Research Part D: Transport and Environment* 41: 88-105 .

Becchio C., Ferrando D.G., Fregonara E., Milani N., Quercia C., Serra V. (2015). The cost-optimal methodology for evaluating the energy retrofit of an ex-industrial building in Turin. *Energy Procedia* 78: 1039-1044.

Becchio C., Ferrando D.G., Fregonara E., Milani N., Quercia C., Serra V. (2016). The cost-optimal methodology for the energy retrofit of an ex-industrial building located in Northern Italy. *Energy and Buildings* 127: 590-602.

Bottero M., Bravi M., Mondini G., Talarico A. (2017). Buildings energy performance and real estate market value: An application of the spatial auto regressive (SAR) model. In S. Stanghellini *et al.* (Eds.), Appraisal: From Theory to Practice. Green Energy and Technology, Springer, Berlin, Germany .

Boussabaine A., Kirkham R. (2004). *Whole Life-Cycle Costing: Risk and Risk Responses*; Blackwell Publishing: Oxford, UK.

Bromilow F.J., Pawsey M.R. (1987). Life cycle cost of university buildings. *Construction Management and Economics* 5(4): 3-22.

Bull J., Gupta A., Mumovic D., Kimpian J. (2014). Life cycle cost and carbon footprint of energy efficient refurbishments to 20th century UK school buildings. *International Journal of Sustainable Built Environment* 3(1): 1-17.

Cabeza L.F., Rincón L., Vilariño V., Pérez G., Castell A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews* 29: 394-416.

Capital Projects Advisory Review Board (2013). Life Cycle Cost Analysis and Energy Efficiency. Washington, USA .

Cetiner I., Özkan E. (2005). An approach for the evaluation of energy and cost efficiency of glass façades. *Energy and Buildings* 37(6): 673-684.

Chapman R.J. (2001). The Controlling Influences on Effective Risk Identification and Assessment for Construction Design Management. *International Journal of Project Management* 19: 147-160 .

Chau K.W. (1995). The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs: empirical evidence from Hong Kong. *Construction Management and Economics* 13(1): 15-21.

Christensen P.N., Sparks G.A., Kostuk K.J. (2005). A method-based survey of life cycle costing literature pertinent to infrastructure design and renewal. *Canadian Journal of Civil Engineering* 32(1): 250-259.

Cole R.J., Sterner E. (2000). Reconciling theory and practice of life-cycle costing. *Building Research & Information* 28(5/6): 368-375.

Coscia C., Curto R. (2017) Valorising in the Absence of Public Resources and Weak Markets: The Case of Ivrea, the 20th Century Industrial City. In S. Stanghellini *et al.* (Eds.), Appraisal: From Theory to Practice. Green Energy and Technology, Springer, Berlin, Germany.

Curto R., Fregonara E. (1999). Decision tools for investments in the real estate sector with risk and uncertainty elements. *Jahrbuch für Regionalwissenscharft* 19: 55-85.

D'Alpaos C., Bragolusi P. (2018). Buildings energy retrofit valuation approaches: state of the art and future perspectives. [Approcci valutativi alla riqualificazione energetica degli edifici: stato dell'arte e futuri sviluppi]. *Valori e Valutazioni* 20: 79-92.

Da Silva Pereira E.J., Pinho J.T., Galhardo M.A.B., Macêdo W.N. (2014). Methodology of risk analysis by Monte Carlo Method applied to power generation with renewable energy. *Renewable Energy* 69: 347-355.

Daneshkhah A., Stocks N.G., Jeffrey P. (2017). Probabilistic sensitivity analysis of optimised preventive maintenance strategies for deteriorating infrastructure assets. *Reliability Engineering & System Safety* 163: 33-45.

Daniotti B., Hans J., Lupica Spagnolo S. (2010a). *An international Service Life Database: the grid definition for an actual implementation of Factor Methods and Service Life prediction.* In: Proceedings of CIB World Congress 2010, Salford Quays, UK.

Daniotti, B., Paolini R., Lupica Spagnolo, S. (2010b). *La valutazione della Vita Utile in fase di progetto: l'implementazione del metodo fattoriale mediante griglie su base prestazionale*. In; Proceedings of 9th Convegno Nazionale ISTeA, Livorno, Italy.

Dattilo C., Negro P., Landolfo R. (2010). An Integrated Approach for Sustainability (IAS): Life Cycle Assessment (LCA) as a Supporting Tool for Life Cycle Costing (LCC) and Social Issues. *Sustainable Building Affordable to All,* Technical University of Lisbon, Lison, Portugal.

Davies H., Wyatt D. (2005). *Appropriate use of the ISO 15686-1 factor method for durability and service life prediction*. In: Proceedings of the International Conference On Durability of Building Materials and Components, Lyon, France.

Davis Langdon Management Consulting (2007). Life Cycle Costing (LCC) as a Contribution to Sustainable Construction: A Common Methodology—Final Methodology.

Davis Langdon Management Consulting (2007). Life Cycle Costing (LCC) as a Contribution to Sustainable Construction: Guidance on the use of the LCC Methodology and its application in public procurement. .

De Angelis E. *et al.* (2013). LCA and LCC based energy optimization of building renovation strategies. In: *Proceeding of SB13 Graz - Sustainable buildings construction products & technologies.* Graz, Austria.

De Jong P., Arkesteijn M. (2014). Life cycle costs of Dutch school buildings. *Journal of Corporate Real Estate* 16(3): 220-234.

Del Giudice V., De Paola P., Manganelli B., Forte F. (2017). The monetary valuation of environmental externalities through the analysis of real estate prices. *Sustainability* 9(2) 229.

Department of Energy - DOE (2014). Life Cycle Cost Handbook Guidance for Life Cycle Cost Estimate and Life Cycle Cost Analysis. Department of Energy (DOE): Washington, DC, USA.

Di Giuseppe E., Iannaccone M., Telloni M., Qualglini E., D'orazio M. (2016). Development of probabilistic methodology for LCC assessment of building retrofit measures. In: *Proceedings of the Colloqui.AT.e 2016—Convegno Ar.Tec.* Matera, Italy.

Di Giuseppe E.; Iannaccone M.; Telloni M.; Di Perna, C. (2017). Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: Methodology and application example. *Energy and Buildings* 144: 416-432 .

Di Giuseppe E., Massi A., D'Orazio, M. (2017). Impacts of Uncertainties in Life Cycle Cost Analysis of Buildings Energy Efficiency Measures: Application to a Case Study. *Energy Procedia* 111: 442-451.

Di Stefano T. (2002). *Valutazione di un insediamento (Ecoparco Industriale) tramite il Life Cycle Costing*. Master Thesis, Politecnico di Torino .

Edwards P., Bowen P. (1998). Risk and risk management in construction: a review and future directions for research. *Engineering, Construction and Architectural Management* 5(4): 339-349.

Ehlen M.A. (1997). Life-Cycle Costs of New Construction Materials. *Journal of Infrastructure Systems* 3(4): 129-133.

Ellingham I., Fawcett W. (2007). *New Generation Whole-Life Costing. Property and construction decision-making under uncertainty*. Taylor & Francis e-Library, Abingdon, UK.

Emblemsvåg J. (2003). *Life-Cycle Costing: Using Activity-Based Costing and Monte Carlo Methods to Manage Future Costs and Risks.* Wiley: New York, NY, USA.

Ergonul S. (2005). Economic analysis of a shopping center in seismic zone. *Building and Environment* 40(11): 1526-1532.

Ergonul S. (2006). A probabilistic approach for economic analysis of a shopping center in seismic zone. *Civil Engineering and Environmental Systems* 23: 57-63.

European Committee for Standardization (CEN), Standard EN ISO 15459:2007, Energy performance of buildings - Economic evaluation procedure for energy systems in buildings, European Committee for Standardization: Brussels, Belgium, 2007.
European Committee for Standardization (CEN). Standard EN ISO 15643-2: 2011. Sustainability of Construction Works—Assessment of Buildings—Part 2: Framework for the Assessment of Environmental Performance; European Committee for Standardization: Brussels, Belgium, 2011.
European Committee for Standardization (CEN). Standard EN ISO 15643-4: 2011. Sustainability of Construction Works—Assessment of Buildings—Part 4: Framework for the Assessment of Economic Performance; European Committee for Standardization: Brussels, Belgium, 2011.
European Committee for Standardization (CEN). Standard EN ISO 16627: 2015. Sustainability of Construction Works—Assessment of Economic Performance of Buildings—Calculation Methods; European Committee for Standardization: Brussels, Belgium, 2015.
European Parliament, Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU; European Parliament: Brussels, Belgium, 2012.
European Parliament. Directive 2010/31/EU of the European Parliament and of Council of 19 May 2010 on the energy performance of buildings (recast); Official Journal of the European Union: Brussels, Belgium, 2010.
European Parliament. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC e 2010/30/EU and repealing Directives 2004/8/EC e 2006/32/EC; Official Journal of the European Union: Brussels, Belgium, 2012.
European Parliament. Directive 2018/844/EU of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency; Official Journal of the European Union: Brussels, Belgium, 2018.
Fabbri K., Tronchin L., Tarabusi. (2014). Energy Retrofit and Economic Evaluation Priorities Applied at an Italian Case Study. *Energy Procedia* 45: 379-384.
Fente J., Knutson K., Schexnayder C. (1999). *Defining a beta distribution function for construction simulation*. In: Proceedings of the 1999 Winter Simulation Conference. Phoenix, AZ, USA, 5-8 December 1999.
Ferreira J., Duarte Pinheiro M., de Britoc J. (2015). Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction - A Portuguese benchmarking. *Journal of Building Engineering* 3: 114-126.
Flanagan R., Norman, G. (1983). *Life Cycle Costing for Construction*. Royal Institution of Chartered Surveyors: London, UK.
Flanagan R., Kendell A., Norman G., Robinson G.D. (1987). Life cycle costing and risk management. *Construction Management and Economics* 5: 53-71.
Frangopol D.M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance* 7(6): 389-413.
Fregonara E., Curto R., Grosso M., Mellano P., Rolando D., Tulliani J.M. (2013). Environmental Technology, Materials Science, Architectural Design, and Real Estate Market Evaluation: A Multidisciplinary Approach for Energy-Efficient Buildings. *Journal of Urban Technology* 20: 57-80. .
Fregonara E., Giordano R., Rolando D., Tulliani J.M. (2016). Integrating Environmental and Economic Sustainability in New Building Construction and Retrofits. *Journal of Urban Technology* 23: 3–28.
Fregonara E. (2017a). Methodologies for supporting sustainability in energy and buildings. The contribution of Project Economic Evaluation. *Energy Procedia* 111: 2-11.
Fregonara E., Lo Verso V.R.M., Lisa M., Callegari G. (2017b). Retrofit scenarios and economic sustainability. A case-study in the Italian context. *Energy Procedia* 111: 245-255.

Fregonara E., Giordano R., Ferrando D.G., Pattono S. (2017c). Economic–environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage. Buildings 7(3): 65.

Fregonara E., Ferrando D.G., Pattono S. (2018a). Economic-environmental sustainability in building projects: introducing risk and uncertainty in LCCE and LCCA. *Sustainability* 10(6), 1901.

Fregonara E., Ferrando D.G. (2018b). How to Model Uncertain Service Life and Durability of Components in Life Cycle Cost Analysis Applications? The Stochastic Approach to the Factor Method. *Sustainability* 10(10): 3642.

Galbusera M.M., de Brito J., Silva A. (2014). Application of the Factor Method to the prediction of the Service Life of Ceramic External Wall Cladding. *Journal of Performance of Constructed Facilities* 29(3).

Galle W., Vandenbroucke M.; De Temmerman N. (2015). Life Cycle Costing as an Early Stage Feasibility Analysis: The Adaptable Transformation of Willy Van Der Meeren's Student Residences. *Procedia Economics and Finance* 21: 14-22.

Gaspar P.L., de Brito J. (2008). Service life estimation of cement-rendered facades. *Building Research & Information* 36(1): 44-55.

Gluch P., Baumann H. (2004). The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. *Building and Environment* 39(5): 571-580.

Grillo M.C., Frattari A., Dalprà M. (2013). Industrial Estate retrofitting: selection of sustainable strategies using MCA. In: *Extended Proceeding of Central Eur*ope towards Sustainable Building 2013: Sustainable Building and Refurbishment for Next Generations. Prague, Czech Republic.

Goh B.H., Sun Y. (2016). The development of life-cycle costing for buildings. *Building Research & Information* 44: 319-333.

Gundes S. (2016). The Use of Life Cycle Techniques in the Assessment of Sustainability. *Procedia - Social and Behavioral Sciences* 216: 916-922.

Guoguo L. (2009). *Integration of LCA and LCC for decision making in sustainable building industry*. Chalmers University of Technology, Gothenburg, Sweden.

Gustafsson S.I., Karlsson B.G. (1988). Why is life-cycle costing important when retrofitting buildings. *International Journal of Energy Research* 12: 233-242.

Gustafsson S.I.; Karlsson B.G. (1989). Life-cycle cost minimization considering retrofits in multifamily residences. *Energy and Buildings* 14, 9-17.

Gustafsson S.I.; Karlsson B.G. (1991). Window retrofits, interaction and life-cycle costing. *Applied Energy* 39(1): 21-29.

Haddad S., Alkass S., Haghighat F. (2008). *An Environmental and Economic Total Life Cycle Costing Methodology and Design Support Tool for Buildings.* In: Proceedings of CIB W055 - W065 Joint International Symposium, Edinburgh, UK.

Han G., Srebric J., Enache-Pommer E. (2014). Variability of optimal solutions for building components based on comprehensive life cycle cost analysis. *Energy and Buildings* 79: 223-231.

Hang Y., Qu M., Zhao F. (2012). Economic and environmental life cycle analysis of solar hot water systems in the United States. *Energy and Buildings* 45: 181-188.

Hochschorner E., Noring M. (2011). A case study with environmental LCC in the Swedish building and construction sector. In: *Proceeding of 6th World Sustainable Building Conference*, Helsinki, Finland.

Heijungs R., Settanni E., Guinée J. (2013). Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. *The International Journal of Life Cycle Assessment* 18: 1722-1733.

Heralova R.S. (2014). Life Cycle Cost Optimization Within Decision Making on Alternative Designs of Public Buildings. *Procedia Engineering* 85: 454-463.

Hovde P.J., Moser K. (2004). *Performance based methods for Service Life Prediction - State of the Art Reports*. CIB Report, Publication 294, Rotterdam, Netherlands.

Ihm P., Krarti M. (2012). Design optimization of energy efficient residential buildings in Tunisia. *Building and Environment* 58: 81-90.

Ilg P., Scope, C., Muench, S., Guenther, E. (2017). Uncertainty in life cycle costing for long-range infrastructure. Part I: leveling the playing field to address uncertainties. *The International Journal of Life Cycle Assessment* 22(2): 277-292.
International Organization for Standardization. ISO 15686-1:2000, Building and constructed assets – Service Life planning – Part 1: General principles; International Organization for Standardization: Geneva, Switzerland, 2000.
International Organization for Standardization. ISO 15686-2:2001, Building and constructed assets – Service Life planning – Part 2: Service Life prediction procedures; International Organization for Standardization: Geneva, Switzerland, 2001.
International Organization for Standardization. ISO 15686-5:2008, Buildings and Constructed Assets—Service-Life Planning—Part 5: Life Cycle Costing; ISO/TC 59/CS 14; International Organization for Standardization: Geneva, Switzerland, 2008.
International Organization for Standardization. ISO 15686-7:2006, Building and constructed assets – Service Life planning – Part 7: Performance Evaluation for Feed-back of Service Life data from practice; International Organization for Standardization: Geneva, Switzerland, 2006.
International Organization for Standardization. ISO 15686-8:2008, Building and constructed assets – Service Life planning Part 8: Reference Service Life and Service Life estimation; International Organization for Standardization: Geneva, Switzerland, 2008.
International Organization for Standardization. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Principles and Framework; ISO/TC 207/CS 5; International Organization for Standardization: Geneva, Switzerland, 2006.
Islam H., Jollands M., Setunge S. (2015). Life cycle assessment and life cycle cost implication of residential buildings - A review. *Renewable and Sustainable Energy Reviews* 42 129-140.
Islam H., Jollands M., Setunge S., Haque N., Bhuiyan M.A. (2015). Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings. *Energy and Buildings* 14(1): 250-263.
Italian Organization for Standardization. UNI 11156-3: 2006, Valutazione della durabilità dei componenti edilizi. Metodo per la valutazione della durata (vita utile); Italian Organization for Standardization (UNI): Milan, Italy, 2006.
Jafari A., Valentin V., Russell M. (2014). Probabilistic Life cycle Cost Model for Sustainable Housing Retrofit Decision-Making. In: *Proceedings of the International Conference on Computing in Civil and Building Engineering*. Orlando, FL, USA.
Johnson D. (1997). The Triangular Distribution as a Proxy for the Beta Distribution in Risk Analysis. *Journal of the Royal Statistical Society. Series D - The Statistician* 46(3): 387-398.
Kapp M.J., Girmscheid G. (2005). *Risk based life cycle cost analysis model for comparable life cycle project delivery decision taking.* In: Proceedings of the 3rd International Structural Engineering and Construction Conference, Shunan, Japan.
Kartam N.A., Kartam S.A. (2001). Risk and its management in the Kuwaiti construction industry: a contractors' perspective. *International Journal of Project Management* 19(6): 325-335.
Kendall A.; Keoleian G.A.; Helfand G.E. (2008). Integrated Life-Cycle Assessment and Life-Cycle Cost Analysis Model for Concrete Bridge Deck Applications. *Journal of Infrastructure Systems* 14(3): 214-222.
Kim Y.D., Cha H.S., Kim K.R., Shin D.W. (2011). Evaluation Method of Green Construction Technologies Using Integrated LCC and LCA Analysis. *Korean Journal of Construction Engineering and Management* 12(3): 91-100.
Kirk, S.J., Dell'Isola, A.J. (1995). *Life cycle costing for design professionals*. McGraw-Hill, New York, NY, USA.
Kishk M., Al-hajj A. (2000). A fuzzy model and algorithm to handle subjectivity in life cycle costing based decision-making. *Journal of Financial Management of Property and Construction* 5(1-2): 93-104.
Kishk M., Al-Hajj A. (2001). An innovative approach to integrating the analysis of uncertainty into life cycle costing. In: Proceedings of the first international conference of Innovation in Architecture, Engineering and Construction, Loughborough, UK .

Kishk M., Al-Hajj A., Pollock R., Aouad G., Bakis N., Sun M. (2003). Whole Life Costing in Construction: A State of the Art Review; RICS Foundation: London, UK.

Kishk M. (2004). Combining various facets of uncertainty in whole-life cost modelling. *Construction Management and Economics* 22(4): 429-435.

Kneifel J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *Energy and Buildings* 42(3): 333-340.

König H., Kohler N., Kreissig J., Lützkendorf T. (2010). *A Life Cycle Approach to Buildings. Principles, Calculations, Design Tools*. Detail Green Books: Regensburg, Germany.

Kovacic I., Zoller V. (2015). Building life cycle optimization tools for early design phases. *Energy* 92(3-1): 409-419.

Krarti M., Deneuville A. (2015). Comparative evaluation of optimal energy efficiency designs for French and US office buildings. *Energy and Buildings* 93: 332-344.

Lam J.C. (1993). Energy-Efficient Measures and Life Cycle Costing of a Residential Building in Hong Kong. *Journal Architectural Science Review* 36: 157-162.

Leigh S.B., Won J.S. (2004). A Case Study for Design Decisions on Building Service System using LCC Analysis. *Environmental Engineering* 3(1): 77-84.

Lijing G., Borong L., Yingxin Z., Daojin G., Mingxing H., Jiazi G. (2008). Integrated assessment method for building life cycle environmental and economic performance. *Building Simulation* 1(2): 169-177 .

Liu R., Smartz B.W., Descheneaux B. (2015). LCCA and environmental LCA for highway pavement selection in Colorado. *International Journal of Sustainable Engineering* 8(2): 102-110.

Liu L., Rohdin P., Moshfegh B. (2016). LCC assessments and environmental impacts on the energy renovation of a multi-family building from the 1890s. *Energy and Buildings* 133: 823-833.

Mahlia T.M.I., Abdul Razak H., Nursahida M.A. (2011). Life cycle cost analysis and payback period of lighting retrofit at the University of Malaya. *Renewable and Sustainable Energy Reviews* 15(2), 1125-1132.

Maio C., Schexnayder C., Knutson K., Weber S. (2000). Probability distribution function for construction simulation. *Journal of Construction Engineering and Management* 126: 285-292.

Mangialardo A., Micelli E. (2017). La partecipazione crea valore? Modelli di simulazione per la valorizzazione dal basso del patrimonio immobiliare pubblico. *Valori e Valutazioni* 19: 41-52. .

Markeset T., Kumar U. (2001). R&M and Risk-Analysis Tools in Product Design, to Reduce Life-Cycle Cost and Improve Attractiveness. In: Proceedings annual reliability and maintainability Symposium. Philadelphia, PA, USA.

Marshall, H.E. (1999). *Sensitivity Analysis*. Dorf, R.C. (Eds), Technology Management Handbook; CRC Press: New York, NY, USA.

Marszal A.J., Heiselberg P. (2011). Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. *Energy* 36(9): 5600-5609.

Menassa C.C. (2011). Evaluating sustainable retrofits in existing buildings under uncertainty. *Energy and Buildings* 43(12): 3576-3583.

Menconi M.E., Grohmann D. (2014). Model integrated of life-cycle costing and dynamic thermal simulation (MILD) to evaluate roof insulation materials for existing livestock buildings. *Energy and Buildings* 81: 48-58.

Menendez J.R.; Gharaibeh N.G. (2017). Incorporating Risk and Uncertainty into Infrastructure Asset Management Plans for Pavement Networks. *Journal of Infrastructure Systems* 23(4) .

Milić V., Ekelöwa K., Moshfegh B. (2018). On the performance of LCC optimization software OPERA-MILP by comparison with building energy simulation software IDA ICE. *Building and Environment* 128: 305-319.

Mistry M., Koffler C., Wong S. (2016). LCA and LCC of the world's longest pier: a case study on nickel-containing stainless steel rebar. *The International Journal of Life Cycle Assessment* 21(11): 1637-1644.

Mok C.K., Rao Tummala V.M. (1997). Leung, H.M. Practices, barriers and benefits of risk management process in building services cost estimation. *Construction Management and Economics* 15: 161-175.

Moser K., Edvardsen C. (2002). *Engineering Design Methods for Service Life Prediction*. In: Proceedings of the 9th International Conference on the Durability of Building Materials and Components, Brisbane, Australia.

Nilsson J., Bertling L. (2007). Maintenance Management of Wind Power Systems Using Condition Monitoring Systems-Life Cycle Cost Analysis for Two Case Studies. *IEEE Transactions On Energy Conversion* 22(1): 223-229.

Norris G.A. (2001). Integrating life cycle cost analysis and LCA. *The International Journal of Life Cycle Assessment* 6(2): 118-120.

Novick D. (1990). Life-Cycle Considerations in Urban Infrastructure Engineering. *Journal of Management in Engineering* 6: 186-196.

Ochoa L., Hendrickson C., Scott M.H. (2002). Economic Input-output Life-cycle Assessment of U.S. Residential Buildings. *Journal of Infrastructure Systems* 8(4): 132-138.

Oduyemi O., Okoroh M., Fajana O.S. Risk assessment methods for life cycle costing in buildings. *Sustainable Buildings* 1: 9-18.

Ouyang J., Ge J., Hokao K. (2009). Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. *Energy Policy* 37(1): 140-149.

Padgett J.E., Dennemann K., Ghosh J. (2010). Risk-based seismic life-cycle cost–benefit (LCC-B) analysis for bridge retrofit assessment. *Structural Safety* 32(3): 165-173.

Pandey M.D., van der Weide J.A.M. (2017). Stochastic renewal process models for estimation of damage cost over the life-cycle of a structure. *Structural Safety* 67: 27-38.

Plebankiewicz E., Zima K., Wieczorek D. (2016). Life cycle cost modelling of buildings with consideration of the risk. *Archives of Civil Engineering* 62(2): 149-166.

Ristimäki M., Säynäjoki A., Heinonen J., Junnila S. (2013). Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy* 65(15): 168-179.

Rosato P., Valcovich E., Stival C.A., Berto R., Cechet G. (2016). Le coperture piane con inverdimento estensivo su edifici esistenti. Parte Seconda—Aspetti economici. *Valori e Valutazioni* 16: 5-27.

Ruparathna R.; Hewage H.; Sadiq R. (2017). Economic evaluation of building energy retrofits: A fuzzy based approach. *Energy and Buildings* 139: 395-406.

Salem O., AbouRizk S., Ariaratnam S. (2003). Risk-based Life-cycle Costing of Infrastructure Rehabilitation and Construction Alternatives. *Journal of Infrastructure Systems* 9(1): 6-15.

Scala E. (2013). *Valutazione del life-cycle costing di tecniche per l'isolamento termico dell'edificio in ambito residenziale*. Master Thesis, Politecnico di Torino.

Schade J. (2007). *Life cycle cost calculation models for buildings.* In: Proceedings of 4th Nordic Conference on Construction Economics and Organisation: Development Processes in Construction Mangement. Luleå, Sweden .

Schmidt, W.P. (2003). Life Cycle Costing as Part of Design for Environment: Business Cases. *The International Journal of Life Cycle Assessment* 8: 167-174.

Scope C., Ilg P., Muench S., Guenther, E. (2016). Uncertainty in life cycle costing for long-range infrastructure. Part II: guidance and suitability of applied methods to address uncertainty. *The International Journal of Life Cycle Assessment* 21(8): 1170-1184.

Sekhar, S.C., Toon, K.L.C. (1998). On the study of energy performance and life cycle cost of smart window. *Energy and Buildings* 28(3): 307-316.

Shapiro, K.G. (2001). Incorporating costs in LCA. *The International Journal of Life Cycle Assessment* 6(2): 121-123.

Silva A., de Brito J., Gaspar P.L. (2016). Stochastic Approach to the Factor Method: Durability of Rendered Façades. *Journal of Materials in Civil Engineering* 28(3): 04015130.

Sobanjo, J. O. (1999). *Facility life-cycle cost analysis based on fuzzy set theory*. In M. A. Lacasse & D. J. Vanier (Eds.), Durability of building materials and components 8. Ottawa: NRC Research Press.

Steen B. (2005). Environmental costs and benefits in life cycle costing. *Management of Environmental Quality: An International Journal* 16(2): 107-118.

Sun Y., Carmichael D.G. (2018). Uncertainties related to financial variables within infrastructure life cycle costing: a literature review. *Structure and Infrastructure Engineering* 14: 1233-1243.

Tabrizi, A., Sanguinetti, P. (2015). Life-cycle cost assessment and energy performance evaluation of NZEB enhancement for LEED-rated educational facilities. Advances in Building Energy Research, 2015, 9(2), 267-279.

Tajani F., Morano P., Di Liddo F., Ntalianis K., Guarnaccia C., Mastorakis N. (2018). *Energy retrofit assessment through automated valuation models: An Italian case study*. In: AIP Conference Proceedings, 2nd International Conference on Mathematical Methods and Computational Techniques in Science and Engineering; Cambridge; UK.

Thiebat F. (2010). Integrazione tra LCA e LCC in edilizia: sviluppo di un modello di valutazione economico-ambientale basato sul ciclo di vita. *Il Progetto Sostenibile.*

Thiebat F. (2012). LCC evaluation of building components including environmental impacts. In: *Abstract Book 6th SETAC World Congress/SETAC Europe 22nd Annual Meeting*. Berlin, Germany.

Thiebat F. (2016). Uno strumento di analisi a supporto di valutazioni strategiche per il recupero e la rifunzionalizzazione di aree dismesse. *TECHNÈ* 12: 238-244.

Udawattha C.; Halwatura R. (2017). Life cycle cost of different Walling material used for affordable housing in tropics. Case Studies. *Construction Materials* 7: 15-29.

Uygunoğlu T., Keçebaş A. (2011). LCC analysis for energy-saving in residential buildings with different types of construction masonry blocks. *Energy and Buildings* 43(9): 2077-2085.

Van Gelder L., Janssen H., Roels S. (2014). Probabilistic design and analysis of building performances: Methodology and application example. *Energy and Buildings* 79: 202-211.

Wang N., Chang Y.C., El-Sheikh A. (2012). Monte Carlo simulation approach to life cycle cost management. *Structure and Infrastructure Engineering* 8: 739-746.

Wang Q., Holmberg S. (2015). A methodology to assess energy-demand savings and cost effectiveness of retrofitting in existing Swedish residential buildings. *Sustainable Cities and Society* 14: 254-266.

Ward, S.C., Chapman, C.B. (1995). Risk-management perspective on the project lifecycle. *International Journal of Project Management* 13: 145-149.

Warren, J.L., Weitz, K.A. (1994). Development of an Integrated Life-Cycle Cost Assessment Model. In: *Proceedings of IEEE International Symposium on Electronics and The Environment*, San Francisco, CA, USA.

Wiguna I.P.A., Scott S. (2006). Relating risk to project performance in Indonesian building contracts. *Construction Management and Economics* 24(11): 1125-1135.

Witt E., Lill I., Nuuter T. (2015). Comparative Analysis of Current Guidance for the Evaluation of Building Retrofit Investments. *Procedia Economics and Finance* 21: 321-328.

Woodward, D.G. (1997). Life cycle costing - Theory, information acquisition and application. *International Journal of Project Management* 15: 335-344.

Wong N.H., Tay S.F., Wong R., Ong C.L., Sia A. (2003). Life cycle cost analysis of rooftop gardens in Singapore. *Building and Environment* 38(3): 499-509.

Zou P.X.W., Zhang G., Wang J. (2006). *Identifying Key Risks in Construction Projects: Life Cycle and Stakeholder Perspectives*. In: Proceedings of the Pacific Rim Real Estate Society Conference, Auckland, New Zealand.